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STUDY OF A LARGE OPTICAL/INFRARED TELESCOPE SCHEME

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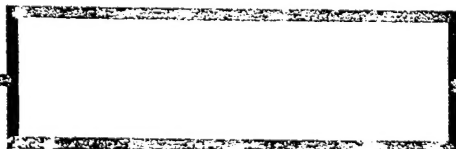
Zhou Bifang, Zhao Peiqian



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STUDY OF A LARGE OPTICAL/INFRARED TELESCOPE SCHEME

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ABSTRACT

In this paper, the study of a scheme of a large telescope array is presented. As an example, a large telescope scheme consisting of six 2.16m telescopes, based on the 2.16m optical telescope completed last year is studied. It can be operated both in visible and IR wavelength regions in three modes: 1. as a unit 2.16m telescope which can be operated at the prime focus, Cassegrain focus, and Coude focus; 2. as an incoherent array for the visible array wavelength region; 3. as a phase array. In section 2, a preliminary design for an incoherent telescope array is given. Six fibers, each with a length of about 20m and a core diameter of 65micrometers are used to link the prime focus and the beam transfer system. Six fibers are also used to guide the light beam to a common detector. The techniques of improving the transmittance of the system are described.

In section 3, the relation between the optical path different (OPD) compensation and the obtainable phased field of view (FOV) are discussed first. Then, a scheme of coherent telescope array is studied in three aspects; the distribution of the telescope, beam transfer, and optical

delay line, and beam combination. The advantages and disadvantages of the coherent telescope array with large aperture at visible wavelengths are discussed.

Finally, we point out the advantages of the telescope array we proposed in this paper from the standpoints of technological, economical, and astronomical efficiencies.

Key words: Astronomical telescopes, telescope array, synthesis aperture telescope.

I. INTRODUCTION

The keys to solving many fundamental astronomical problems are large light-correction capability and imaging with high resolving power. Since the advent of the astronomical telescope, astronomers have pooled their efforts in the two above-mentioned purposes. Especially in the recent decade and more, some new techniques were developed to achieve these two purposes, such as, spot interference technique, self-adaptive optical technique, active optical technique, and long baseline technique. China successfully developed a 2.16m astronomical optical telescope. How to proceed in the next step is one of the central problems long discussed by Chinese astronomers. As China has the capability of fabricating the largest diameter 2.16m telescope, by citing an example this article presents a multi-optical/infrared telescope (referred to as telescope array in the following text), consisting of six telescopes of regular hexagonal layout with six 5.29m telescopes in equivalent diameter, and the longest baseline being 100m. The telescope array can be coherently synthesized into a telescope with synthesized diameter and can also be noncoherently synthesized for superimposition of light intensity. Meanwhile, each secondary telescope can operate independently.

I. Noncoherent Array

Before discussing the noncoherent array, the authors assume the availability of six secondary telescopes with optical

parameters based on 2.56m optical telescopes made in China [1], as shown in Fig. 1. In the prismatic system of the secondary telescopes, a self-adaptive optical system can be placed (or the system may not be required). In the infrared waveband (such as $\lambda=2.2$ micrometers), the self-adaptive optical system can have complete compensation for atmospheric disturbances; in the visible light region, incomplete compensation can be achieved.

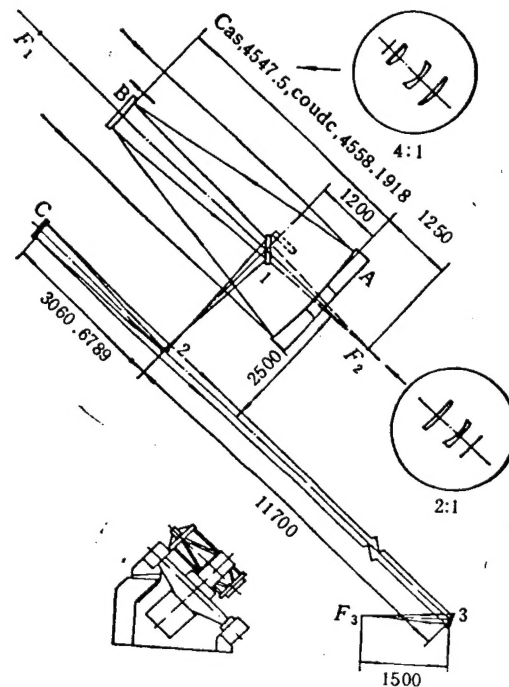


Fig. 1. Optical layout of the Chinese 2.16m telescope

As shown in Fig. 2, a 15-m-long optical fiber connects the main focus F_1 of the telescope $f/3$ to a focus F_2 of parabolic-surface length M_1 in the vicinity of the focus of the prismatic axis. After collimation of the light beam, the beam passes along a vacuum pipe to the central laboratory. In the central laboratory, the parallel optical beams are focused by the parabolic-surface mirror M_2 to the end of another 10-m-long optical fiber. In this way, after six light paths passed, respectively, through the optical fiber to a detector (such as a

spectrograph with prismatic axis), the vacuum pipe is shared by these light beams during coherent synthesis of the vacuum pipe and the light beams. There are two modes for coupling between optical fiber and telescope [2]: one is direct coupling between the telescope focus and the optical-fiber end; and the other is coupling between the exit pupil of the telescope and the end of the optical fiber. At present, we do not know which mode is better (Zhao Peiqian, one of the authors, is doing this work). However, in this scheme, it seems better for direct coupling of the main focus of $f/3$ to be the end of the optical fiber because at that time the focusing ratio of optical fiber attenuates and approaches zero [3], thus not requiring the coupling length and the coupling efficiency will be higher. Let us assume that the average seeing is 2", then the diameter of visual image of the main focus is 63micrometers; thus the core diameter of the optical fiber is 65micrometers. One of the authors, Zhao Peiqian, conducted spectral attenuation of some Chinese-made optical fiber. As an example, taking a 20-m-long doped quartz optical fiber with 50micrometer core diameter, its transmissibility is 83 to 85% in the 3000 to 3400Angstrom region, 83 to 92% in the 3400-4000Angstrom region, and higher than 92% in the 4000-8500Angstrom region. To reflect reflective attenuation at the end of the optical fiber, a glass wedge 0.5mm thick (using the same material as the optical fiber) is placed at the end of the optical fiber. The surface of the glass wedge has anti-reflection coating, as a feasible design scheme shown in Fig. 3.

III. Coherent Synthesis--Large Infrared Synthesis Aperture Telescope

As is well known, as wavelength is decreased, the technical conditions are more and more difficult to carry out interference. In this section, a large infrared telescope interference array is presented mainly to observe the infrared waveband. With later maturing of other conditions, gradual extension to the visible light waveband will be feasible.

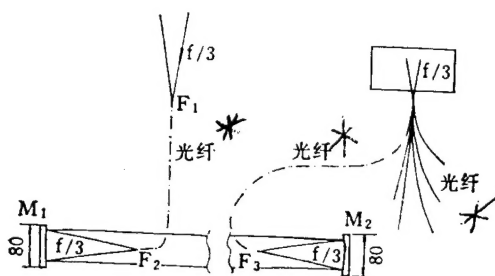


Fig. 2. Incoherent telescope array linked by optical fibers
Key: * - optical fiber

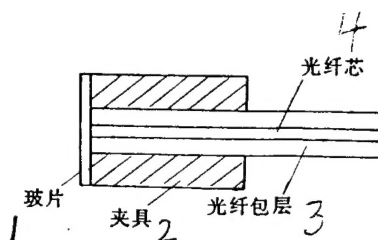


Fig. 3. Structure of optical fiber end

Key: 1 - glass wedge
2 - clamp 3 - cladding layer of optical fiber
4 - optical fiber core

A. Optical path compensation and coherent visible field

For coherence of a dual telescope, the optical path difference is shown in the following equation as generated on the beam convergent length by heavenly bodies at a distance of infinity with their light passing through the two telescopes:

$$D = L_0 \sin(\theta + \alpha) + \Delta - d \cos(M\alpha) - l \sin(M\alpha). \quad (1)$$

when the visible field angle alpha is very small, the above equation can be expanded into:

$$D = L_0 \sin \theta + \Delta - d + (L_0 \cos \theta - lM)\alpha + \frac{1}{2}(dM^2 - L \sin \theta)\alpha^2 + \dots \quad (2)$$

In the equation, L_0 is the length of the baseline; theta is the zenith distance; d is the axial distance between the telescope exit pupils; l is the longitudinal distance from one telescope exit pupil to the other; delta is the optical path difference between the two telescope interiors. If compensation is made only for light on the axis, that is, the zero level optical path compensation, with alpha being equal to zero, then

$$D = L_0 \sin \theta + \Delta - d = 0. \quad (3)$$

Now, if $d=0$ and $l=0$ (overlapping of two exit pupils), and at this stage, if $\lambda=4\text{ micrometers}$, $L_0=100\text{m}$, and $\theta=60^\circ$, the effective visual field is approximately $0''005$ for the remaining optical path difference smaller than $\lambda/4$. If we let the summation of alpha terms be equal to 0, then the first level

optical path compensation is conducted, thus obtaining the compensation condition:

$$l = \frac{L_0 \cos \theta}{M}. \quad (4)$$

Here, if $d=0$, then when $\lambda=4\mu\text{m}$, $L_0=100\text{m}$, $M=66$, and $\theta=60^\circ$, the effective visual field is approximately 2" for the remaining optical path difference being smaller than $\lambda/4$.

To obtain greater coherent (phase sharing) visual field, second-level optical path compensation should be conducted; that is, the summation of α^2 terms is 0. Thus, we have obtained the compensation conditions as:

$$d = \frac{L_0 \sin \theta}{M^2}. \quad (5)$$

Here, if $\lambda=4\mu\text{m}$, $L_0=100\text{m}$, $M=66$, and $\theta=60^\circ$, then the effective visual field is approximately 10" for the remaining optical path difference being smaller than $\lambda/4$.

B. Scheme of Synthesis Aperture Telescope

1) Layout of telescope

In the interference array, many factors should be considered in the telescope layout, such as whether or not the telescopes are moved, whether there are field restrictions, the direction of the wind, (u,v) coverage, detection mode, requirements of noncoherent operation mode, and future expansion. In actual design, a compromise may be made among the various factors, or secondary factors may be sacrificed to satisfy the requirements of the main factors. However, whatever the (u,v) coverage, optical path compensation, or noninterference operation, or other requirements, a very flexible scheme is to move the telescopes. In the interference operating mode, moving the telescopes can not only achieve optical path compensation, but also can execute the so-called hypersynthesis. Meanwhile, during noncoherent imaging, telescopes can be moved very close to each other to reduce optical path transfer. The scheme of moving telescopes is very reliable to intermediate and small-aperture telescope arrays.

However, currently it is not practical for large-aperture telescopes because of technical limitations. By combining with the practical conditions in China, this article selects a homogeneously distributed form (as shown in Fig. 4) of six telescopes distributed over a 100m-diameter circle. Mainly, the following aspects are considered:

(1) There is better (u,v) coverage. Figure 5 is the (u,v) graph when the zenith distance is 0.

(2) There are some identical space frequencies with a definite abundance of space frequencies.

(3) Longitudinal direction expansion can be conducted later on with such arrays with greater light concentrating ability and better (u,v) coverage. The future expansion does not affect the layout in the central laboratory.

(4) Maximum resolving power can be obtained in three different directions, and the graphic resolving power has better symmetry.

(5) During noncoherent synthesis, the lengths of various optical paths are basically equal to each other.

The length of the baseline is one of the most important interference array parameters; the longer the baseline, the greater is the angular resolving power. However, the telescopes become more sparsely located and (u,v) coverage is more incomplete. The coherent visual field is inversely proportional to the baseline length L_0 ; the longer the baseline, the smaller the coherent visual field that can be obtained, except for the south-to-north direction, otherwise a faster compensation rate of the optical path is required. Therefore, there is no east-to-west placement on three diagonals of a hexagon in the scheme.

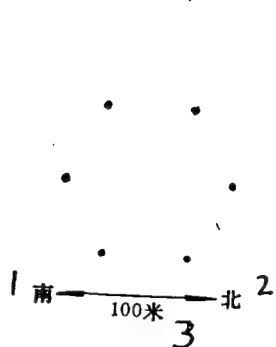


Fig. 4. Distribution of telescopes
KEY: 1 - south 2 - north
3 - meters

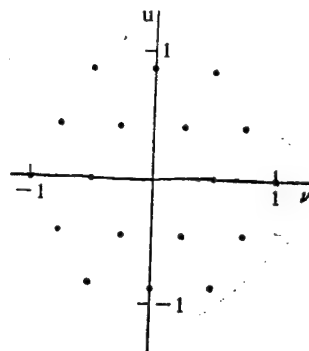


Fig. 5. (u,v) plane for an
object at zenith

2) Optical transfer and optical delay line

Fig. 6 shows an optical transfer route of a synthesis aperture optical/infrared telescope system. Exiting from the focus of the prismatic axis of each secondary telescope, light from $f/45$ is converted to parallel rays entering the transfer pipe and optical delay line. Let us assume that the maximum zenith distance is $\theta = 60^\circ$, the maximum optical path compensation is approximately 43.3m. When adopting a one-time rearward reflection, the maximum movement of the optical path compensator is 21.7m. After passing through a reflective mirror, the light beam from the delay line enters into the beam-convergent telescope. Fig. 7 shows an optical conversion system in the vicinity of the focus of the prismatic axis. After passing through a dichroic beam splitter, the prismatic-axis light beam is divided into two: the visible light is used to detect the wave surface of the self-adaptive optical system. While the infrared light is used for interference, the function of field lens MF is to image the entrance pupil of the telescope in the vicinity of the entrance pupil of the light beam synthesis telescope. The off-axis parabolic surface converts the

prismatic-axis light beam into parallel rays. Let us assume that the aperture compression ratio of the light beam of a secondary telescope is $M=100$, then the aperture of the transmitted light beam is 21.6mm.

As previously pointed out, to proceed with zero-level optical path compensation in order to let the optical path difference be zero on the axes of various sub-optical paths, the optical delay line, moving of telescopes, or a combination of the two can be adopted. The advantages of moving the telescope are to reduce the intermediate refraction of the delay line, and the optical energy loss caused by reflective optical elements. M. Viekanand [4,5] et al. studied the movement rule of telescopes when moving the telescope in executing the optical path compensation, in the coherent situation of dual and multiple telescopes. However, for large-aperture telescopes, during the observation process there are very difficult problems, such as telescope precision, as well as orientation and tracking in the process of rapid motion and telescope motion. Based on feasible conditions in China, the article adopts the optical delay line method in executing zero-level optical path compensation. Later on, the method of combining the moving of telescope and optical delay line is not excluded in the future. Moreover, there are different forms of optical delay line; the authors adopted the so-called cat-eye type optical path compensator, which consists of a principal parabolic surface lens, and a secondary lens located at the focal point of the principal lens. The best advantage is that the direction of the exiting light beam is not sensitive to inclination and translation of the compensator. Fig. 8 shows the structure of the compensator. The secondary lens is a thin lens with variable radius of curvature in order to adjust the axial direction position of the exit pupil formed by the field lens MF, thus executing second-level optical-path compensation. Based on Eq. (5), the authors adopt maximum

$\theta=60^\circ$, $\dot{M}=100$, $L_0=100\text{m}$, then the axial-direction adjustment range of the exit pupil is $d=8.66\text{mm}$.

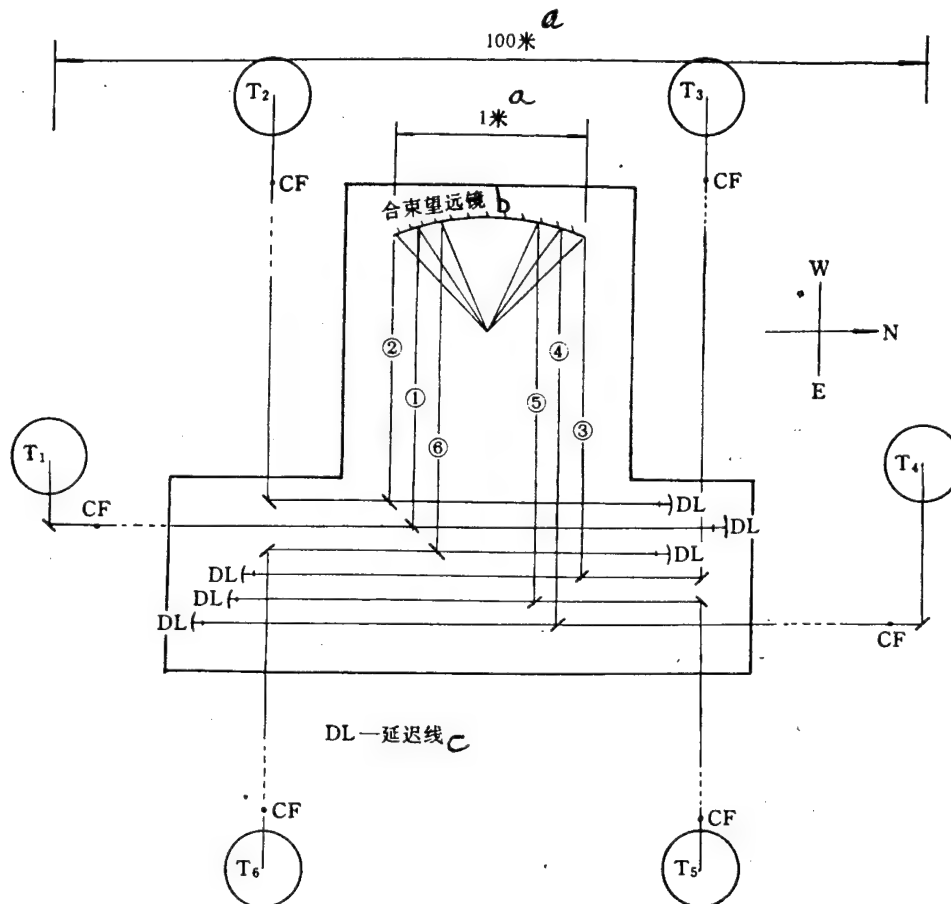


Fig. 6. Optical beam transfer path of the synthesis aperture optical telescope scheme

KEY: a - meter b - beam-convergent telescope
c - delay line

3) Optical beam synthesis

Optical beam synthesis can be subdivided into synthesis of image surface, and synthesis within the exit pupil plane. This

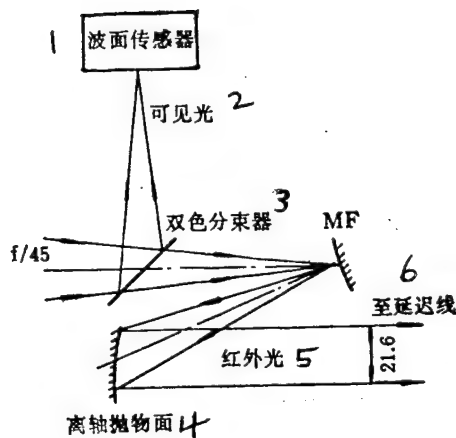


Fig. 7. Optical beam conversion near prismatic axis focus
KEY: 1 - wave surface sensor
2 - visible light 3 - dichroic beam splitter 4 - off-axis parabolic surface
5 - infrared light 6 - to delay line

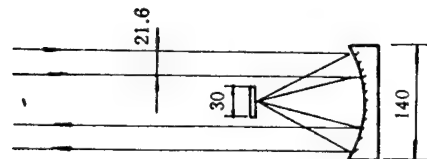


Fig. 8. Cat-eye optical delay line

scheme adopts the image surface synthesis. Generated by various secondary telescopes, overlapping of the Airy disks produces fringes. A surface array detector detects the oscillation amplitude and phase of the visibility of these interference fringes, thus achieving restructuring of the image. Fig. 9 is a scheme of carrying out the image surface synthesis. From six delay lines, after the parallel light beams enter the entrance pupil plane of the beam-convergent telescope, synthesis comes into being within the focal plane of the beam-convergent telescope. By changing the relative positions of the exit pupils of various secondary telescopes entering into the entrance pupil plane of the beam-convergent telescope, we can satisfy different detection types and astronomical purposes. For example, when conducting observation of a plane optical source, in order to obtain a cophased visual field, we know that the first level optical path compensation should be conducted while maintaining

the relative directions among the entrance pupils and the relative directions among the exit pupils. In other words, the horizontal distance among exit pupils of the secondary telescopes should satisfy the relationship equation $l = L_0 \cos \theta / M$. This process is carried out by moving the plane lenses MP and MQ. The aperture of a beam-convergent telescope is determined by the first-level optical path compensation conditions. When the longest baseline is $L_0 = 100\text{m}$, the aperture of the beam-convergent telescope should be $l_{\max} = L_0 / M$. When $M = 66$, $l_{\max} = 1.52\text{m}$. When $M = 100$, then $l_{\max} = 1\text{m}$. In another example, only observation of a very small visual field is conducted without conducting the first level optical path compensation, but with rearrangement of exit pupil based on requirements. Meanwhile, there are two feasible synthesis modes: one is paired synthesis among optical beams in order to carry out phase locking without requiring a beam-convergent telescope in this case. Another method is to arrange into a straight line for exit pupils within the entrance pupil of a beam-convergent telescope, as shown in Fig. 10; the interference fringes are perpendicular to the straight line. Beam splitter observation can be conducted by placing a light splitting narrow gap in the direction perpendicular to the interference fringes, thus utilizing the fringe information to the maximum extent.

4) Discussion of interference of visual light

Interference of visible light has been successful in small-aperture telescopes. For large-aperture telescopes, the main difficulty is on the effect of atmospheric disturbances, not the fabrication technique in making the interference array. Except in the future that self-adaptive optics can be applied to the visible light waveband of large-aperture telescopes to carry out complete compensation of atmospheric disturbances, a star image is a single spot; the interference is also interference of a single spot, then the aperture of the secondary telescope can have sufficient exploitation of its functions, and the

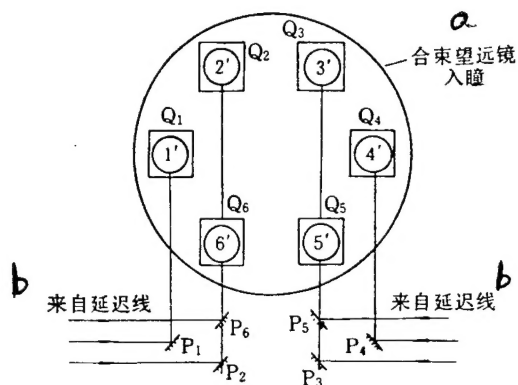


Fig. 9. Beam combining system on the image plane
KEY: a - entrance pupil of beam-convergent telescope
b - from delay line

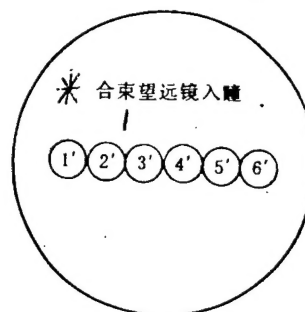


Fig. 10. Beam combining configuration when exit pupils of the telescopes are in line
KEY: * - entrance pupil of beam-convergent telescope

sensitivity of the interference array of the telescopes is the highest. Otherwise, the interference array of large-aperture telescopes will operate in multi-spot interference state, and the interference fringes within each spot drift unceasingly. Hence, the sensitivity of the interference array is very low. In particular, when the observed waveband is very wide, the maximum sensitivity is almost totally unrelated to aperture. For heavenly bodies such that a single telescope is unable to discriminate, the signal-to-noise ratio increases only in proportion to $D^{1/6}$ of the telescope aperture. During observation of a narrow waveband, its sensitivity increases with D^2 . Hence, even in the future, when self-adaptive optics will be unable to completely compensate for atmospheric disturbances in the visible light region, this scheme can still be used to conduct observation of visible light of a narrow waveband with better sensitivity.

IV. Conclusions

It is imperative that China should build large optical/infrared telescopes. The problem is what telescopes to build, and how large should the telescopes be. In this article, a way is pointed out for building large telescopes in China with presentation of a scheme. This scheme is more adaptable to China's status with the following manifestations: 1) time buffering. A 2.16-m telescope can be used for observation after its completion. When two such telescopes are built, interference operations can be conducted. Then one after one of such telescopes can be added into an array. 2) Buffering of expenditures: this point is apparent because we do not require such big first-time investment of building larger-aperture telescopes. 3) Technical shortcuts: this point is very important because we don't require to spend many years of learning and relearning and of research into such techniques abroad by expending large sums in order to develop greater-aperture telescopes. This step is skipped, but proceed simultaneously with fellow-researchers abroad on a new step, while achieving the purpose achieved by astronomers of other nations.

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